

Electromagnetic Launch Optical Telemetry Feasibility Study

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Electromagnetic Launch Optical Telemetry

Feasibility Study

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Abstract—Results of a preliminary study to evaluate the feasibility of optical telemetry on an EM launched projectile are discussed. At issue are the relative intensities of the optical noise received in the MCL catch tank from the muzzle flash versus the narrowband optical signal levels generated from tiny emitters onboard a projectile after being launched in the MCL. Two narrowband optical signal emitters are compared with the muzzle flash: a high intensity light emitting diode (AND190HAP LED) and a vertical cavity surface emitting laser (VCSEL). Optically filtered photo-detector responses of the broadband muzzle flash received in the catch tank after launch were spectrally analyzed in this work. The muzzle flash levels in 10-nm bands were observed to have effective intensities: $\sim 1.1 \text{ mW}\cdot\text{m}^2$ centered at 610 nm and $\sim 1.0 \text{ mW}\cdot\text{m}^2$ centered at 840 nm. The optical noise of the muzzle flash was found to overwhelm the received optical signal of the 612-nm LED by a factor of 20—indicating such a device will be unfeasible. On the other hand, the $0.86\text{-mW}\cdot\text{m}^2$ effective intensity of a single 850-nm VCSEL—packaged with a domed-lens in a TO-46—was about the same as the muzzle flash. The low-frequency spectral content of the optically filtered muzzle flash and the narrow optical beam of the VCSEL indicate several tens of dB improvement in S/N will likely be gained by telemetering information at frequencies of 500-1000 MHz with a single VCSEL. Advantages of the VCSEL over the LED—significant improvements in: luminosity, optical bandwidth, modulation bandwidth, physical size, and power dissipation—suggest that such a device will prove feasible as an optical source on an EM launched projectile used for telemetry. It is recommended that these potential advantages be investigated next under high-g EM launch conditions using an array of VCSELs as an optical source to digitally telemeter frequency modulated information in the UHF band.

1. Introduction

The Hardened Subminiature Telemetry Sensor System (HSTSS) has demonstrated the feasibility of using microwave techniques to telemeter information from onboard a high-g projectile [1]. Optical telemetry techniques may offer advantages over microwave techniques. Spatial resolution—which can be a factor in stealth communication with the projectile, for example—is much higher at optical wavelengths. Optical telemetry has been successfully demonstrated in transmitting on-board measurements during the initial stages of the launch phase at velocities up to 2 km/s and accelerations up to 105 kG [2], but increases in bore opacity prevented optical transmission after the first few milliseconds of launch.

The basic system schematic for optical telemetry used to convey on-board diagnostics conducted in [2] is shown in Figure 1. The launch package contained a sensor, electronics, and a light source. The light information was transmitted down the bore, reflected off a mirror and collected by a telescope, which amplified both the narrow-band optical signal and the broadband optical noise of the muzzle flash generated by the electric launch. The muzzle flash was mostly blocked by the armature while in-bore, and the light collected was optically filtered to further reduce the optical noise before it was detected by a photo-multiplier tube (PMT) and recorded with a storage oscilloscope.

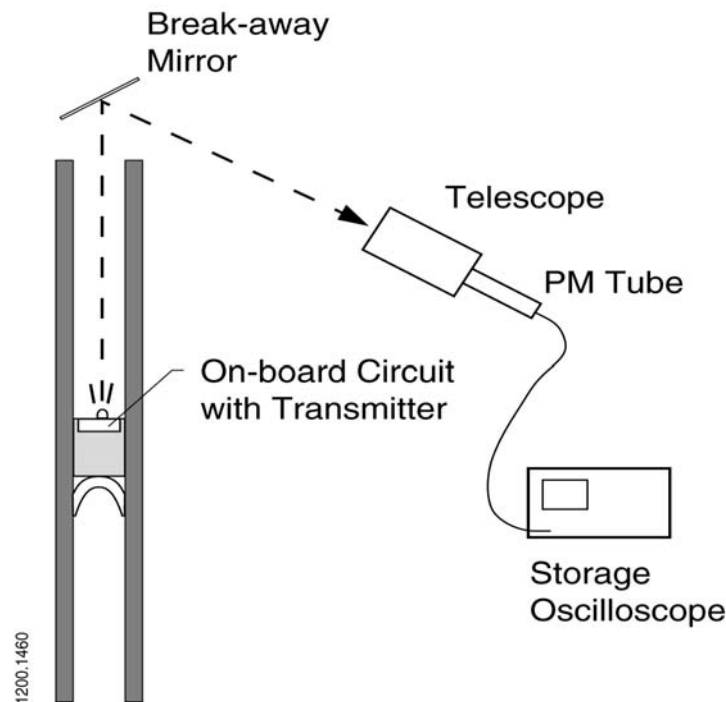


Figure 1. System schematic diagram showing in-bore optical transmitter, external mirror, and method of data collection used in [2].

The principal remaining issue in [2] was the opacity in the bore, which increased rapidly during the shot and degraded the amplitude of the transmitted signal. It is believed that the increased opacity was caused by a turbulent fluid layer in front of the projectile due to the highly compressed gas while the projectile resided inside the railgun bore. A turbulent fluid layer has a corresponding turbulent index of refraction, which randomly scatters the light signal [3]. After the projectile exits the bore, the thickness of the layer in front of the armature may be reduced significantly, permitting optical transmission to resume.

In this investigation, our objective was to determine the feasibility of telemetering information with light by transmitting it from an EM projectile after it exits the bore. Analysis of the optical noise measurements from the muzzle flash received in the catch tank of the MCL is described in Section 2. In Section 3, analysis is described of the anticipated optical signal levels that can be transmitted from the projectile by the same type of high intensity light emitting diode (LED) used in [2] and that from a vertical

cavity surface emitting laser (VCSEL) suggested to the authors [4]. Recommendations to achieve successful telemetering of information onboard an EM launched projectile are discussed in Section 4.

2. Optical Noise: Muzzle Flash

The basic setup used in this work to obtain optical signal and noise measurements with the MCL is shown in Figure 2. Using the same optical receiving system (telescope, 610-nm optical filter, and PMT) and LED signal source (AND190HAP) as used in [2], our first efforts were devoted to comparing the noise intensities of the muzzle flash received in the catch tank during MCL shot #01031501 [5] with the LED signal intensity transmitted near the muzzle. Two such LED light sources were fixed on the bore axis: one a few inches directly in front of the muzzle and the other inside the catch tank a few inches before the mirror so that both were detectable by the PMT. Throughout the MCL shot, both LED's were repetitively excited at 100 kHz with 2.0- μ s, 100-mA pulses. A 4.0- μ s relative delay between LED pulses provided a distinction between the received optical levels, which were monitored with the recorded PMT voltage responses, as shown in the upper plot of Figure 3. However, the 610-nm optically filtered PMT became saturated by the muzzle flash before the projectile even reached the muzzle at 4.5 ms, as shown in the lower plot of Figure 3. Therefore, a combination of significantly increased signal levels and reduced noise levels (e.g., received muzzle flash levels) was found to be necessary to optically telemeter measurements on the MCL.

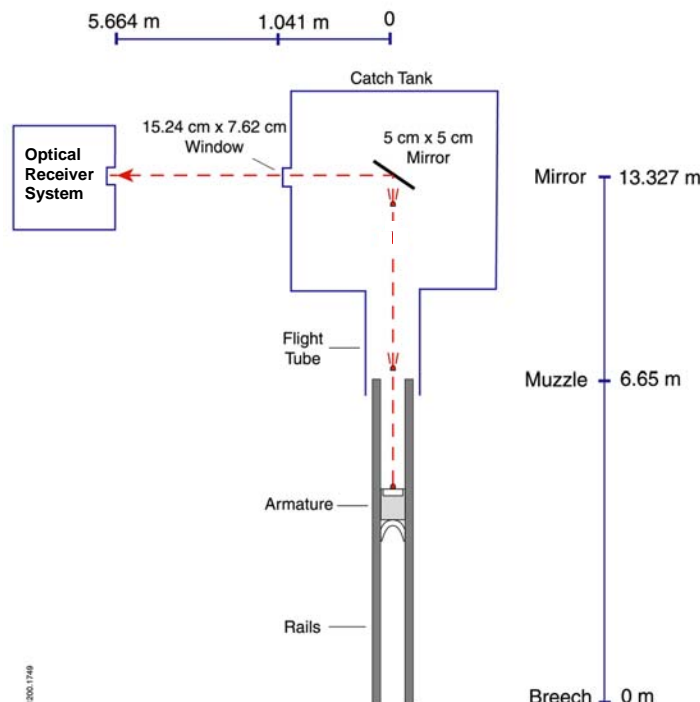


Figure 2. Experimental setup to obtain optical data in the MCL after the armature has exited the muzzle. This system was used to measure the received muzzle flash noise levels. The 5 cm x 5 cm, 1st-surface mirror had a 95% reflectance. The 15.24 cm x 7.62 cm optical window was 1.25 cm thick and had ~80% optical transmittance.

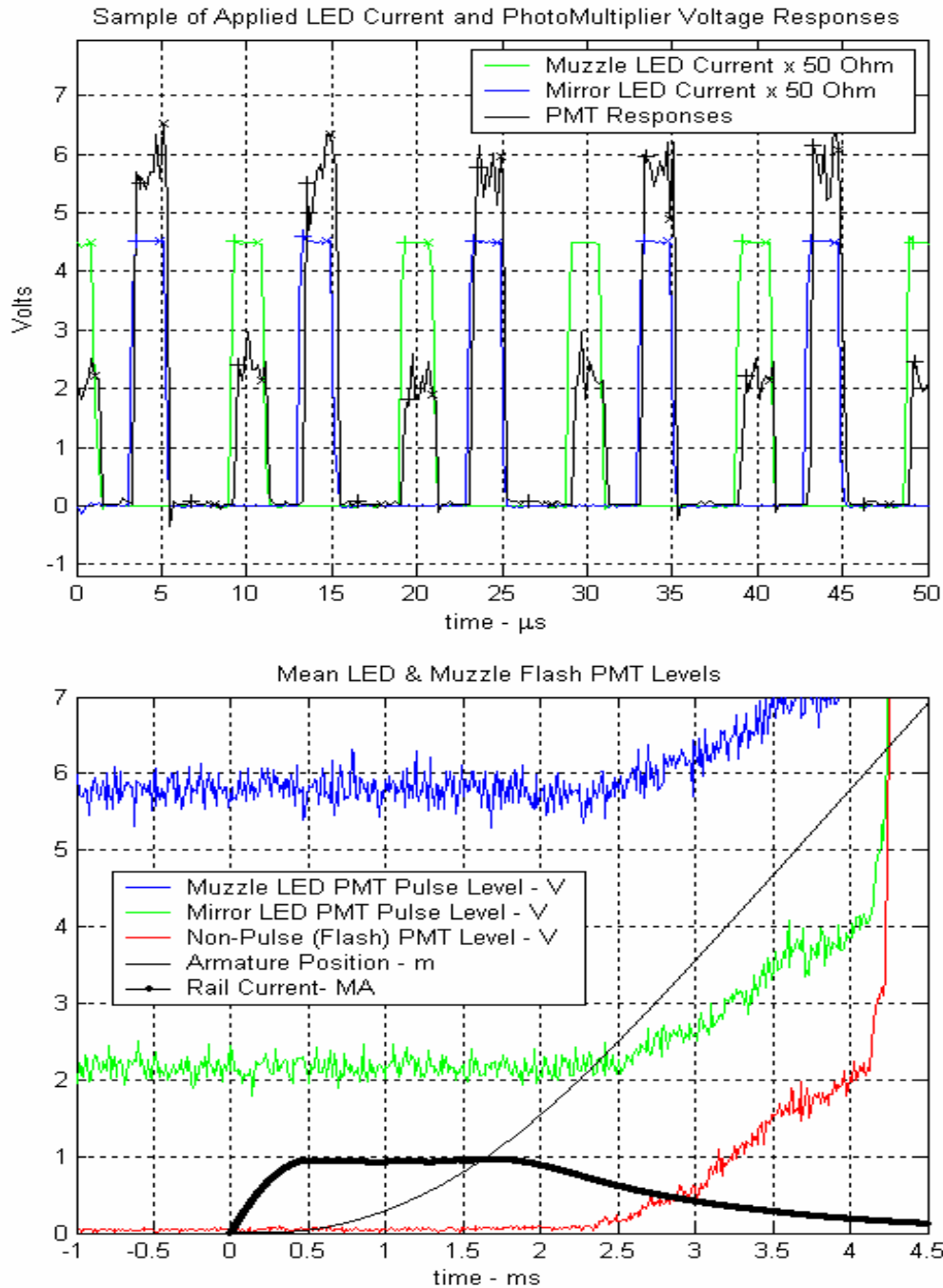


Figure 3. Optical signal levels were transmitted by AND190HAP LEDs fixed just after the muzzle and just before the mirror for MCL shot #01031501. The mean levels were temporally resolved from the known LED current excitations (see upper plot), providing a distinction between optical signals of the LEDs and the optical noise of the muzzle flash. Shown in the lower plot are the mean voltage levels from the PMT used in the optical receiver system, which became saturated by the muzzle flash before the projectile exited the bore ~ 4.5 ms after application of railgun current.

A modified version of the optical receiving system previously used to obtain direct, calibrated measurements of the muzzle flash [6] was used to obtain the current optical noise measurements of the muzzle flash. The receiver consisted of a combination of silicon photo detectors (PDA55) and optical filters. Because the optical signal levels of the 612-nm, high-intensity LED and the 850-nm VCSEL are being investigated in this work, there was interest in the power levels of the optical flash at those wavelengths. Three optical filters with center wavelengths 438 nm, 610 nm, and 840 nm, were available and placed directly in front of the PDA55 detectors, and each had approximately 10-nm half-magnitude full-width bandwidth; a fourth PDA55 detector was used, unfiltered. These detectors have a 3.6 mm × 3.6 mm active area, a 10-MHz bandwidth, a 15-V/mA transimpedance gain, and an optical responsivity of that shown in Figure 4. The optical power transfer coefficients of the detector/filter combinations are listed in Table 1.

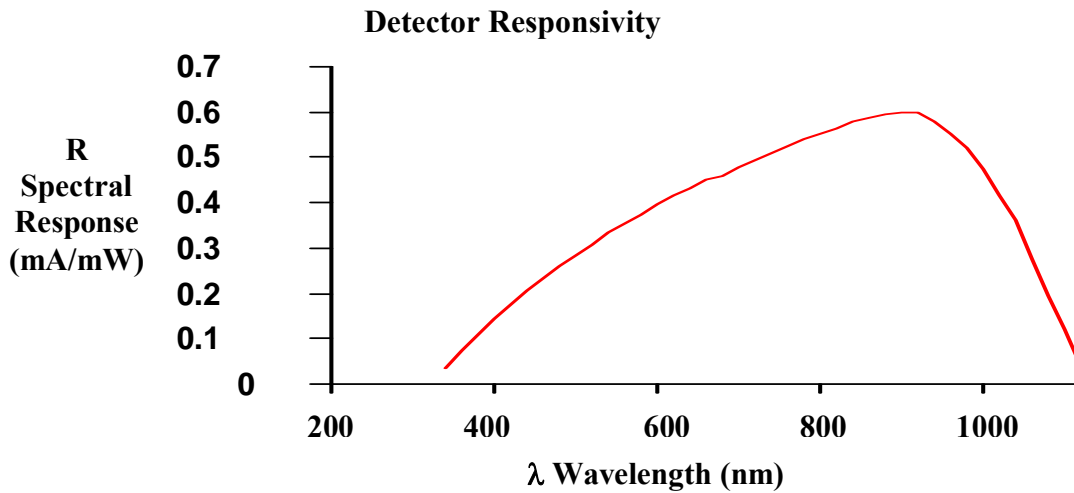


Figure 4. Shown is the optical responsivity $R(\lambda)$ of the ThorLab PDA55-Switchable Gain, Amplified Silicon Detectors. When an optical excitation with power P (mW) and wavelength λ impacts the 3.6 mm x 3.6 mm active area, this detector produces output voltage: $V = 15 \cdot R \cdot P$.

Table I. Optical Power Transfer Coefficients of the Detector/Filter Combinations

Optical Filter Center Wavelength, Bandwidth≈0 nm	PDA55 Optical Power Transfer Coefficient	Filter Band Transmission Factor	Combined Optical Power Transfer Coefficient
438 nm	0.33 mW/V	52%	0.64 mW/V
610 nm	0.165 mW/V	50%	0.33 mW/V
840 nm	0.12 mW/V	58%	0.21 mW/V

The sensitivities of the recording digitizing oscilloscope were set to allow the full dynamic range of the expected optical flash levels to be recorded. The received LED signal levels at these sensitivities under quiescent MCL conditions were far exceeded by the ambient light levels. Therefore, signal measurements were not recorded during optical

noise measurements of the muzzle flash taken for MCL #01050801 [5], where an 874-kA current peak was reached at 3.1 ms after the onset of the applied current. B-Dot coil measurements indicated that the projectile reached the muzzle at 4.78 ms, having attained an exit velocity of 2.66 km/s; the projectile struck the mirror in the catch tank at 7.32 ms, assuming its velocity remained constant.

Shown in Figure 5 are the recorded photo-diode responses of the optical system, with times also shown when the projectile reached the muzzle and mirror—calculated from the projectile dynamics determined by B-Dot maxims. The optically filtered responses reveal how the received optical power of the muzzle flash suddenly increased when the projectile exited the muzzle (~ 4.8 ms), and again just before the projectile reached the mirror (~ 7.3 ms), when there was a direct optical path between the armature and optical detectors.

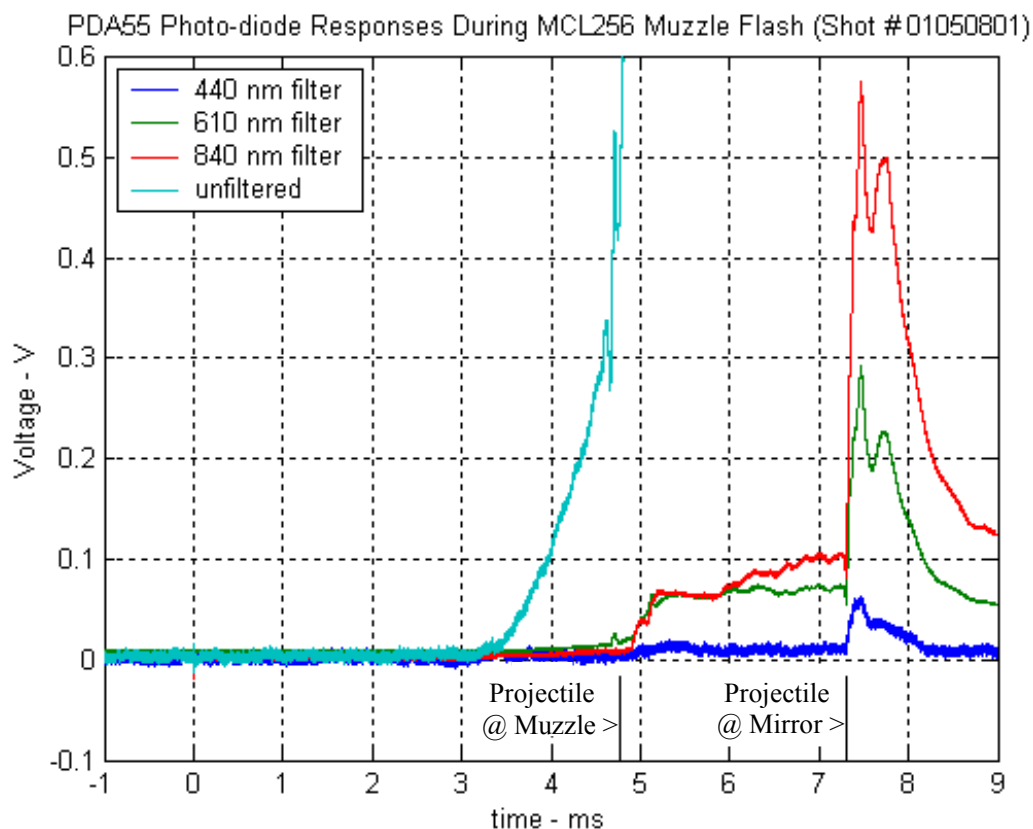


Figure 5. Shown are the optical flash responses obtained for MCL #01050801.

The amplitude settings of the oscilloscope were nearly optimal for the 610-nm and 840-nm muzzle flash components and provided the highest resolved levels without saturation. The amplitude setting for the 440-nm component (which had been purposefully selected to be relatively insensitive in case the optical flash levels were significantly brighter than expected [5]) resulted in a relatively noisy 440-nm response due to a digitization error. The response associated with the unfiltered detector became saturated before the projectile reached the muzzle, confirming that the optical flash noise levels are greatly reduced with optical filtering.

Optical signals that are transmitted after muzzle exit will be received in the presence of optical noise due to the muzzle flash. In the present MCL configuration, such signals may be detected during the interval that begins after the projectile reaches the muzzle and ends when it strikes the target (mirror). The received optical power levels of the muzzle flash noise corresponding to the responses in Figure 5 during this interval are shown in the upper plot of Figure 6, with the calculated digital power spectra shown in the lower plot. If the muzzle flash is modeled as an optical point source with square-law spreading, then an optical source intensity may be defined: $I = P \times Z^2$, where P is the received optical power at a distance Z . An effective, band limited optical source intensity of the muzzle flash may be defined using the optically filtered power received by each detector with values increased to account for losses due the optical window ($/0.8$) and mirror reflectance ($/0.95$). Such intensities were determined from the optical power received at $t=7.00$ ms (when the projectile was 85.1 cm from the mirror) in Figure 6; they were $I_{610}=1.1 \text{ mW} \cdot \text{m}^2$ for the 610-nm component and $I_{840}=1.0 \text{ mW} \cdot \text{m}^2$ for the 840-nm component.

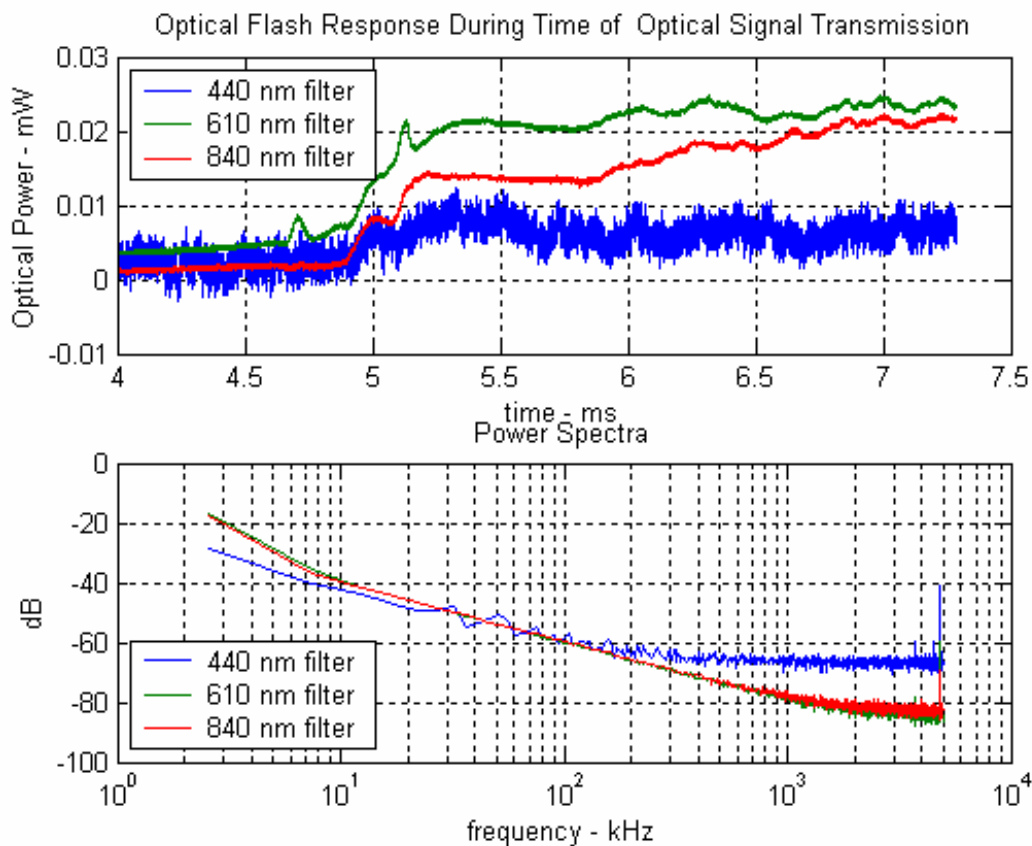


Figure 6. The received optical power levels (upper plot) and corresponding power spectra (lower plot) of the optical flash in the MCL are shown during the interval in which an on-board optical signal would be detected. The large disparity between the low and high frequency components may be exploited in a telemetry system.

The spectra shown in the lower portion of Figure 6 corresponding to the muzzle flash at 440 nm were dominated by digitization noise due to the small dynamic recording range. The more accurate 610-nm and 840-nm power spectra were dominated by the lowest frequency components—with the optical flash components near 3.0 kHz more than 60 dB greater in amplitude than components at frequencies greater than 2.0 MHz. An interesting, but not identified, narrowband oscillation was also present at 4.83 MHz, ~20 dB greater in magnitude than the adjacent components. The wide, 60 dB disparity between the low and high frequency components may be exploited: the signal to noise ratio (S/N) of information transmitted as a high-frequency, frequency-modulated signal may be improved greatly by receiving it using optical telemetry with high-pass filtering. This would significantly reduce the response from low frequency optical noise sources such as the muzzle flash.

3. LED and VCSEL Optical Signal Sources

In this section, the characteristics of the AND190HAP LED and Honeywell VCSEL are investigated for their suitability as an optical signal source after launch on the MCL. In [2], both a laser diode and the AND190HAP LED were used as optical signal emitters on MCL projectiles. The laser diode, repackaged with a lens assembly, produced a bright, well collimated ~1° beam. However, because the laser chip is mounted on the side of an axial post in the laser diode, operation became unstable under railgun acceleration—producing amplitude variations as large as 50% during the launch. The LED emitter proved to be more stable during launch than the laser diode, and it was used for the more successful optical-telemetry EM-launch experiments in [2]. Because of the nature of the AND190HAP LED design, its physically large, 10-mm diameter lens is required in order to focus its 6°, irregular beam. Some improvement in the LED optics was achieved in [2] through diffusing the beam by cutting off the top of the lens, roughening the interface, and then reattaching it with glue. However, this procedure, which also reduces the intensity and degrades the structural integrity of the LED, was not considered further in the present study.

To exceed the optical noise levels of the muzzle flash, optical transmission after projectile-exit requires significantly larger optical signal levels than were necessary in [2], but the optical emitter need only recover from (rather than transmit during) the acceleration of a railgun launch. Neither the AND190HAP LED nor the Honeywell VCSEL have been commercially tested or recommended for their survivability in the high-g launch environment of an EML. However, it is noted that the AND190HAP LED has been observed to survive 105-kg EM launch accelerations [2], and the surface-emitting nature of the VCSEL suggests that such a device may be at least as mechanically stable as the LED.

The VCSEL appears to have many advantages over the LED. In addition to mechanical stability, attributes of an on-board optical signal emitter should include smallness in size, weight, and power requirement, and it should contribute to a large S/N—through high optical output intensity, narrow optical bandwidth, and/or wide modulation bandwidth. Some of the technical information relevant to an EM launched optical transmitter, provided by the commercial distributor and manufacturer of the LED and VCSEL, are listed in Figure 7. Most of the attributes—luminosity, optical bandwidth,

modulation bandwidth, and power dissipation—favor the VCSEL by an order of magnitude. The same is also true for the mass and size of these devices (particularly for the VCSEL in a Pill Pack), as shown by the photographs in Figure 7.






Optical Emitter Attributes	AND190HAP LED	Honeywell		VCSEL	
		TO-46 Flat Window	Pill Pack Flat Window	Pill Pack Dome Lens	TO-46 Dome Lens
					
		SV3637	SV4637	SV2637	SV5637
Mass	1019.5 mg	262.5 mg	33.1 mg	34.0 mg	310.1 mg
Beam Divergence θ degrees:	6°	10°	10°	4°	2°
$\Omega = 2\pi \{1 - \cos(\theta/2)\}$ Steradians:	$8.6 \cdot 10^{-3}$	$24 \cdot 10^{-3}$	$24 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	$0.96 \cdot 10^{-3}$
Typical Luminosity	0.13 mW ($I_F = 20$ mA)	1.5 mW ($I_F = 14$ mA)			
Peak Emission Wavelength	612 nm	850 nm			
Bandwidth (FWHP)	15 nm	0.85 nm			
Modulation Bandwidth	0.1 GHz	10 GHz			
Maximum Power Dissipation P_D	125 mW	20 mW			
Maximum Forward Current I_F	50 mA	20 mA			

Figure 7. Shown is a list of manufacturer's technical characteristics relevant to use as an optical signal source for the LED [7] and VCSEL in different packages [8].

Since high reliability in this application is required for periods of order seconds rather than years, the specified maximum current peaks were exceeded in this investigation by up to a factor of 6 to yield higher luminosity, and both devices performed without incident. Quick-look measurements of the optical levels versus input current of these devices were carried out using an optically filtered PDA55 detector to receive the light at a 25 cm distance. The 610 nm filter was used during measurements of the AND190 LED source and the 840 nm optical filter was used during measurements of a VCSEL source packaged in a T0-46 with a flat window (SV3637). Input current was supplied in 500-ns pulses at a 200 kHz rep-rate, and optical alignment was manually adjusted to obtain the highest response for each sample of current magnitude. The power levels of the optical responses are shown in Figure 8 and indicate that the optically filtered emission received from the SV3637 VCSEL was little more than three times that from the AND190 LED at the same current levels—rather than the order of magnitude increase given in Figure 7.

Although optical filtering is necessary for the EML application, additional measurements without optical filtering were taken, indicating that actual optical output levels were about the same for these devices; the 610 nm and 840 nm filter attenuation factors were measured to be 16 and 60 percent, respectively. Similar measurements, obtained using five AND190 LEDs, resulted in 1.2 percent standard deviation from the 15.8 percent mean value of the measured filter attenuation coefficient, indicating that the optical spectrum of each filter might be narrowly centered about a wavelength differing by 6 nm from the specified value. However, it is more likely that the optical spectrum of

the LED is significantly broader than the 10 nm bandwidth of the optical filter, and most of the light was attenuated.

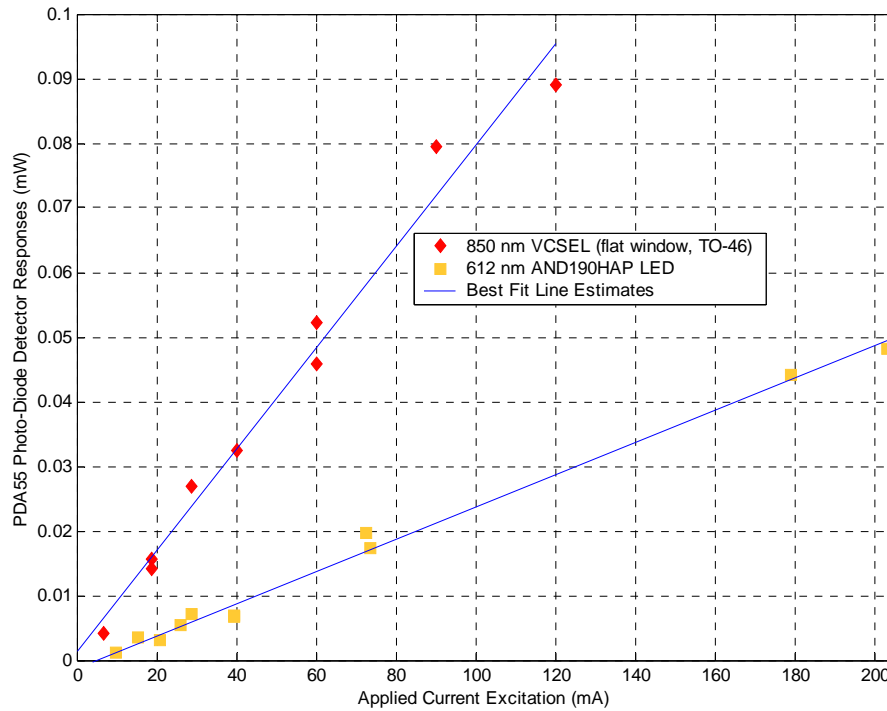


Figure 8. Shown is a plot of measured, optically filtered PDA55 detector responses from the AND190HAP LED and Honeywell VCSEL (SV3637)—at a 25 cm distance as a function of current level.

The narrow optical band of the VCSEL (< 1 nm), nominally centered at 850 nm, was within the 10 nm band of the 840-nm filter, since the measurements confirmed the 60 percent value of the 840 nm filter band transmission factor. The maximum effective source intensities corresponding to the effective muzzle flash intensity were: $0.03 \text{ mW} \cdot \text{m}^2$ for the AND190 LED and $0.056 \text{ mW} \cdot \text{m}^2$ for the SV3637 VCSEL. Both were far too small, relative to the optical noise of the muzzle flash ($I_{610} = 1.1 \text{ mW} \cdot \text{m}^2$ and $I_{840} = 1.0 \text{ mW} \cdot \text{m}^2$), to be a feasible emitter in the MCL. On the other hand, a dramatic improvement in the received signal was observed by focusing a narrow ($\theta=2^\circ$) beam using a VCSEL packaged with a dome lens (SV5637) to improve the directed optical beam intensity. The solid angle Ω of the beam is inversely related with optical intensity and is approximately the square of (small) beam divergence angle θ $\{\Omega=2\pi(1-\cos(\theta/2)) \approx \theta^2 \cdot \pi/4\}$. For a fixed illuminance, the spanning distance increases with the square of θ . These improvements come with the expense of higher optical alignment sensitivity.

Optical measurements at a 37-cm distance indicated that the SV5637 VCSEL packaged with the lens produces maximum effective source intensity of $0.82 \text{ mW} \cdot \text{m}^2$, approaching that of the corresponding muzzle flash noise component. In addition, the narrower beam allows one to increase the optical signal level without increasing the optical noise. This could be accomplished on the MCL up to a 11.5 factor by altering the

configuration to reduce the optical window aperture by this factor while simultaneously repositioning the optical receiving detector closer to the mirror by the root of this factor (3.4). Thus, the optics, mass, and signal strength of the VCSEL appear sufficient for use on board an MCL projectile.

4. Summary and Recommendations

The results of this stationary investigation indicate that, while the high intensity LED will not, a VCSEL packaged with a converging lens should easily meet the S/N conditions required for optical telemetry on a projectile launched by the MCL. The spectral content of the noise of the muzzle flash has been found to be dominant in frequencies below 10 kHz. The optical noise should be exceeded by the signal received from a VCSEL due to several factors. Compared with the high intensity LED, the narrower optical band of the VCSEL allows higher gains due to optical filtering and higher frequency electronic filtering of the signal. Additionally, a higher frequency transmission allows shorter receiving intervals and a larger number of repeated transmissions. The small size, mass, and power requirement of the VCSEL suggests that the use of an array of focused VCSELs will improve signal level and source/receiver alignment sensitivity. The longer wavelength of the infrared VCSEL is less susceptible to high-speed turbulent degradation of the signal. Perhaps the most significant remaining issue is the mechanical stability of the VCSEL in a high-g launch. It is recommended that the VCSEL next be tested under high-g EM launch conditions in an array used to digitally telemeter frequency-modulated information in the UHF band.

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- [7] AND190HAP LED from Purdy Electronics, Sunnyvale, CA.
- [8] Samples supplied by Pritha Khurana, Honeywell, Intl., Richardson, TX.